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Separation Control in a Multistage Compressor Using Impulsive Surface Injection

David W. Wundrow
Ohio Aerospace Institute, Brook Park, Ohio

Edward P. Braunscheidel, Dennis E. Culley, and Michelle M. Bright
Glenn Research Center, Cleveland, Ohio

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David W. Wundrow
Ohio Aerospace Institute, Brook Park, Ohio

Edward P. Braunscheidel, Dennis E. Culley, and Michelle M. Bright
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National Aeronautics and
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Glenn Research Center
Cleveland, Ohio 44135

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David W. Wundrow
Ohio Aerospace Institute
Brook Park, Ohio 44142

Edward P. Braunscheidel, Dennis E. Culley, and Michelle M. Bright
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Control of flow separation using impulsive surface injection is investigated within the multistage environment of a low-speed axial-flow compressor. Measured wake profiles behind a set of embedded stator vanes treated with suction-surface injection indicate significant reduction in flow separation at a variety of injection-pulse repetition rates and durations. The corresponding total pressure losses across the vanes reveal a band of repetition rates at each pulse duration where the separation control remains nearly complete. This persistence allows for demands on the injected-mass delivery system to be economized while still achieving effective flow control. The response of the stator-vane boundary layers to infrequently applied short injection pulses is described in terms of the periodic excitation of turbulent strips whose growth and propagation characteristics dictate the lower bound on the band of optimal pulse repetition rates. The eventual falloff in separation control at higher repetition rates is linked to a competition between the benefits of pulse-induced mixing and the aggravation caused by the periodic introduction of low-momentum fluid. Use of these observations for impulsive actuator design is discussed and their impact on modeling the time-average effect of impulsive surface injection for multistage steady-flow simulation is considered.

INTRODUCTION

The success of localized surface injection at suppressing flow separation from airfoils in external flows has led several groups (1–5) to investigate injection-based flow control on turbomachinery blading. The application of interest here is stator-vane separation control within multistage axial-flow compressors. As with any flow-control approach, localized surface injection will have technological value only if the improved operability it provides outweighs the penalties associated with its implementation.

Two sources of implementation penalties for injection-based flow control are broadly identified: those related to the net amount of injected mass, eg. thermodynamic cycle penalties incurred by aft-stage bleed extraction, and those related to fluidic actuation, eg. auxiliary power requirements and reduced durability. The relative importance of these two sources varies with injection method. Steady injection entails only modest actuation costs but requires fairly large amounts of injected mass to suppress separation (1, 3, 4). Adding a harmonically oscillating component to the injected flow lessens this penalty (while increasing actuation costs) by reducing the net injected mass fraction relative to compressor through flow (3). The limiting form of this approach is synthetic-jet (or zero-net-mass-flux) injection which incurs virtually no injected mass costs but requires high actuation frequencies to be most effective (6).

Impulsive injection, where fluid is discharged only during short bursts separated by periods of rest, provides an apt compromise between steady and synthetic-jet injection. Bons, Sondegaard and Rivir (2) investigated pulsed vortex generator jets on the blades of a linear cascade designed to mimic the flow separation possible in low-pressure turbines at high-altitude cruise. The authors report effective flow control at pulse duty cycles d and repetition rates f as low as 10 percent and 1 Hz, respectively. Culley, Braunscheidel and Bright (5) used impulsive injection to control separation on the embedded stator vanes of a low-speed axial-flow compressor and demonstrate significant reductions in total pressure loss with pulse durations τ as short as 1.5 ms at reduced pulse repetition rates F^+ near unity.

Determination of an optimal pulse duration and repetition rate combination for a given application requires knowledge of the relevant physical processes involved in impulsive-injection based flow control. Bons et al. (2) explained the unexpected effectiveness they observed at low duty cycles and pulse repetition rates as a consequence of the enhanced cross-stream mixing provoked by pulse-generated startup vortices combined with the slow relaxation of the re-energized boundary layer. The much shorter pulse duration and lower injection velocity results of Culley et al. (5) are consistent with this conjecture and further reveal a range of pulse repetition rates (at fixed pulse duration) where the injection-induced separation control remains nearly optimal. The latter result supports the view that the pulse repetition rate is more closely coupled to the boundary-layer relaxation time than to any mixing-enhancement process instigated by the impulsive injection.

Similarities between the impulsive injection considered here and the pulsed jets used to study artificially triggered turbulent spots (7–9) suggest that the boundary-layer response to an isolated injection pulse mimics passage of a turbulent strip. When a periodic train of pulses is considered, the envisioned parallel becomes the flow over an embedded airfoil where turbulent strips are periodically induced by the shed wakes of upstream blades (10). It is known that such wake-induced transition can delay stator-vane separation in multistage compressors (11). The present work explores this analogy to determine its utility at aiding the design of durable, economic flow-control treatments.

The experimental effort begun by Culley et al. (5) is continued here to allow connections to be drawn with the formation and propagation characteristics of turbulent strips and their trailing "calmed" regions. Also revealed by the investigation is a competition between the benefits of pulse-induced mixing enhancement and the adverse effects associated with the periodic introduction of low-momentum fluid. The impact of the experimental findings on impulsive actuator design are considered and an approach to modeling the time-average effect of impulsive injection in multistage steady-flow design codes is discussed.

EXPERIMENTAL SETUP

The experimental investigation is conducted in the NASA Glenn Low-Speed Axial Compressor facility where local surface injection is introduced on a select set of embedded stator vanes. The injection is controlled externally by a high-speed actuation system that allows exploration of a broad range of pulse durations and repetition rates. The increased size and reduced speed of the facility relative to a turbofan core compressor permits detailed intra-stage flow-field surveys which are used to assess the performance of the flow-control system.

Table 1. LOW-SPEED AXIAL COMPRESSOR PARAMETERS

Tip Speed [m/s]	61
Axial Velocity [m/s]	25
Tip Radius [cm]	61.0
Hub Radius [cm]	48.8

Low-Speed Axial Compressor (LSAC)

The LSAC consists of an inlet guide vane and four identical stages designed for accurate low-speed simulation of the rear stages of a high-speed core compressor. Filtered air enters the facility and is conditioned for temperature and turbulence before passing through a calibrated bellmouth and into a long entrance duct where thick end-wall boundary layers typical of an embedded compressor stage develop. The first two stages setup a "repeating-stage" environment for the third stage where most of the research data are taken. The fourth stage serves as a buffer to the exit conditions which are controlled by a throttle valve through which the exiting airflow passes before being discharged into an atmospheric exhaust system. A complete description of the LSAC facility is given in Wasserbauer, Weaver and Senyitko (12). Parameters relevant to the present investigation are given in Table 1.

Overall compressor performance is expressed in terms of the average pressure-rise coefficient ψ and flow coefficient ϕ. The former quantity is determined from inlet and outlet static pressure measurements on the hub and casing while the latter is calculated from static pressure measurements at the bellmouth exit using a previously determined discharge coefficient. All results reported below are obtained at design speed with ψ and ϕ equaling 0.56 and 0.36, respectively. The measurement accuracies are given by Wellborn and Okiishi (13) as ± 1.09 percent for ψ and ± 0.39 percent for ϕ.

The blading used for the current tests is based on a modified version of the Rotor B/Stator B design provided by General Electric for the NASA Energy Efficient Engine program. The stators all have inner shrouds and are sealed at both the hub and tip junctions with the flow path. Details of the blading design are reported in Wisler (14). Blading parameters relevant to the present investigation are given in Table 2.

Individual vane performance is expressed in terms of the total pressure loss coefficient ω computed from area-averaged pressure data acquired upstream and downstream of the vane. Total pressure measurements are made with miniature (1.64 mm) Kiel head probes while 18 degree wedge probes provide the static pressure and flow-angle data. All pressure measurements are made at midgap between the blade rows and are referenced to stagnation conditions recorded in the facility's inlet plenum. Wellborn and Okiishi (13) report a measurement accuracy for ω of ± 2.1 percent.

Table 2. COMPRESSOR BLADING PARAMETERS (MIDSPAN)

	Rotor	Stator
Solidity	1.12	1.38
Aspect Ratio	1.20	1.32
Chord [cm]	10.2	9.4
Stagger [deg]	43	42
Clearance [cm]	0.17	0.07
No. of Blades/stage	39	52
Axial Gap [cm]	2.54	

Figure 1. CAD REPRESENTATION OF A FLOW-CONTROL VANE.

Flow-Control Vanes

The LSAC facility provides simplified access to four stator vanes along the third-stage annulus through a removable casing window. Experimental reconfigurations are thus accomplished without disassembly of the compressor casing by merely removing the window and vanes as a unit. Despite the obvious limitations of changing the blading over such a short segment of the annulus, this approach proved effective at altering the local embedded-vane loading conditions (3, 5).

The flow over the LSAC stator vanes is not prone to strong separation prior to compressor stall. To investigate flow-separation control at reasonable operating conditions, three of the four vanes under the stage three window were installed at increased incidence by setting the stagger angle 4 ± 1 degrees above its design value. The remaining 49 vanes in the stage were left unaltered. Surface pressure measurements indicate that the restaggered vanes remain attached during open-throttle conditions but suffer significant flow separation at the lower flow coefficient considered in this investigation (see Fig. 3). The data suggest that separation begins near mid chord of a restaggered vane and results in a detached flow at the trailing edge. Wake surveys across the full vane passage along with time-average numerical simulations of the modified LSAC show that the separated flow is confined to a spanwise region extending from the hub to about 30 percent of span.

The induced flow separation is addressed by introducing suction-surface injection on two of the three restaggered vanes. The injection is done through a 0.63 mm wide slot located at 35 percent of chord and extending from 10 to 36 percent of span. The slot is pitched 30 degrees downstream relative to the surface tangent to limit injection provoked separation and includes a support web at its midspan to maintain structural rigidity. Wind tunnel studies of an isolated airfoil with suction-surface pressure distribution similar to the restaggered vane show that the region of separated flow lies just downstream of the injection slot under "uncontrolled" conditions. The chosen slot location is therefore an acceptable compromise between injecting too far upstream where a favorable pressure gradient hinders the excitation of a lasting boundary-layer disturbance and injecting too far downstream where the uncontrolled flow is already detached.

The flow-control vanes are designed with the same aerodynamic surfaces and mounting points as the standard LSAC vanes but include the slots and internal flow passages required for injection. The vanes are produced using the rapid prototyping process described in Culley et al. (5). A CAD representation of the flow-control vane is shown in Fig. 1. Note that only the two slot openings nearest the hub (lower-left corner of the figure) were unsealed in the current investigation. Instrumentation ports are included on one of the flow-control vanes to permit static pressure measurements within the injection cavity and along the suction surface at 44 percent of span and 5, 74, 82 and 90 percent of chord. The internal cavity pressure is used to correlate the injection forcing pressure with the injection mass flow. The suction-surface taps are used to monitor the state of separation along the vane surface.

Injected-Mass Delivery System

The injected-mass delivery system describes a series of components located outside the LSAC casing that deliver a measured stream of injection air to the two flow-control vanes in pulses of variable duration and repetition rate. Compressed air from a large-capacity filtered shop supply is reduced to the appropriate pressure (typically 91.7 kPa gauge) using a mechanical regulator before being passed through a mass-flow controller operated in metering mode to obtain the period-averaged mass-flow rate $\dot{m}_{jet}$. At the exit of the mass-flow controller is a large 5500 cm^3 pressure vessel which insulates the instrument from system resonances and serves as an accumulator to provide a stable source pressure p_{acc} for the high-speed solenoid values used to pulse the injection. Two independent supply tubes of 6.33 mm inside

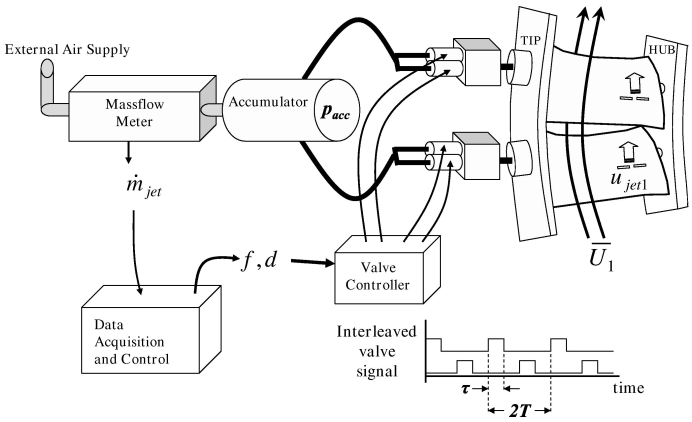

Figure 2. SCHEMATIC OF INJECTED-MASS DELIVERY SYSTEM.

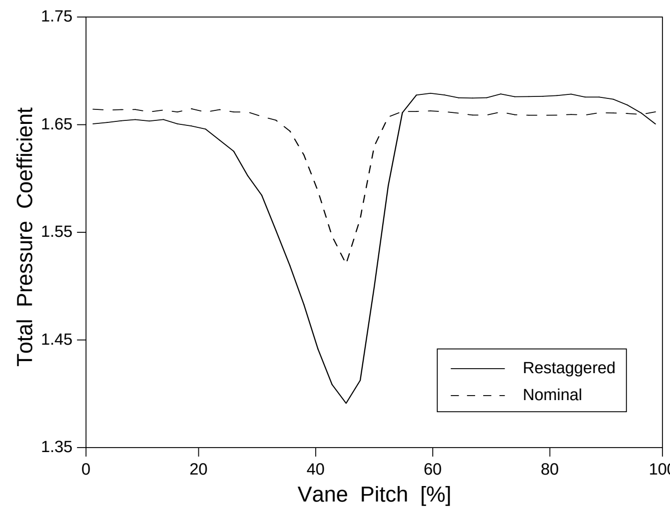

Figure 3. WAKES OF NOMINAL AND RESTAGGERED STATORS.

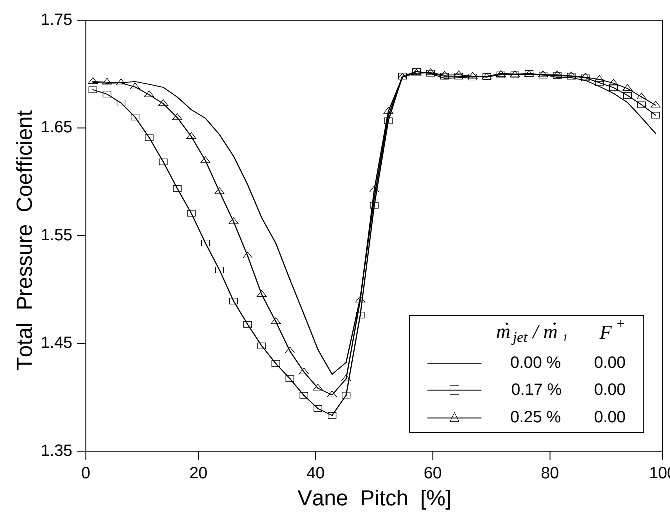

Figure 4. LOW-MOMENTUM STEADY INJECTION RESULTS.

diameter leave the accumulator and branch off to feed the pair of solenoid valves attached to the tip end of each flow-control vane. A schematic drawing of the injected-mass delivery system is given in Fig. 2.

The valves making up each solenoid-valve pair are operated in an interleaved manner with their individual on times 180 degrees out of phase. A resultant T-periodic input to the flow-control vane is then produced by providing a $2T$-periodic signal to each valve. This increases the range of realizable pulse repetition rates while limiting the burden placed on the actuators. The precise response of the solenoid valves is inferred from bench measurements of the injected-flow velocity near the injection slot and static pressure measurements in the injection cavity. The repetition rate f is supplied by a digital signal generator while the pulse duration τ is provided by the valve controller. Both are adjustable and accurate to within a microsecond or better.

EXPERIMENTAL RESULTS

Wake profiles of total pressure behind the stage-three stator vanes are obtained from circumferential surveys taken at 30 percent of span. The baseline for comparison is the restaggered flow-control vane with zero surface injection. The wake profile for this case is shown in Fig. 3 as is the profile for a nominally staggered vane in the same stage but on the opposing side of the compressor. The figure confirms the fully attached state of the nominal vane at the design speed and flow coefficient considered here as well as the significant flow separation occurring along the suction surface of the restaggered vane.

Past Efforts

Using the LSAC facility and identical flow-control vanes (but with injection applied through slot openings extending from 10 to 90 percent of span), Culley et al. (3) show that steady surface injection can re-energize the local boundary layer and reduce the restagger-induced flow separation by providing a constant stream of relatively high-momentum fluid. The injection velocity must be of the order of the mean free-stream speed to fully suppress the separation and as a result fairly large amounts of injected mass are required. Moreover, the results of Ref. (3) show that injecting at too low a velocity actually worsens the separation by introducing additional low-momentum fluid into the already decelerating boundary layer (see Fig. 4).

Culley et al. (3) go on to demonstrate that the detrimental effects associated with the steady injection of low-momentum fluid can be overcome by adding a small harmonically oscillating

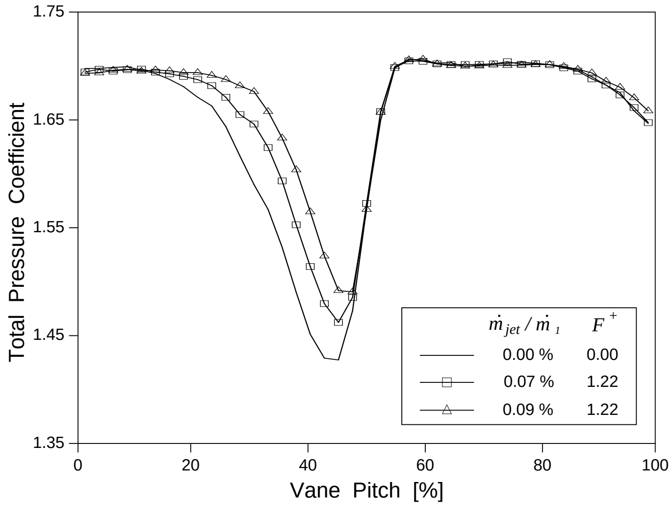

Figure 5. PULSED INJECTION RESULTS AT 50% DUTY CYCLE.

component to the injected flow. Using this approach, the period-averaged injected-mass fraction relative to passage through flow $\dot{m}_{jet}/\dot{m}_1$ required for a given reduction in total pressure loss is less than half that needed for purely steady injection. The unsteady component is believed to aid in re-energizing the local boundary layer by enhancing mixing between the near-wall and free-stream flows. A range of frequencies for the unsteady component of the injection stream was explored – though all approximately order one when normalized by $\bar{U}_1/L$ – and, apart from resonances associated with the injected-mass delivery system, no strong frequency preference was evident.

The success of harmonically modulated surface injection at reducing the net injected mass needed for successful separation control, prompted Culley et al. (5) to try minimizing the steady component of the injected flow. This necessitated replacing the siren value used in the injected-mass delivery system of Ref. (3) with the high-speed solenoid values described above. The injection air could then be delivered in pulses dictated by the on/off times of the solenoid values with negligible leakage. When the on/off times are equal (i.e. the duty cycle is 50 percent), the injection stream approximates the harmonically oscillating component considered previously. The authors demonstrate successful separation control using impulsive surface injection at 50 percent duty cycle and a net injected mass fraction significantly lower than that required with the harmonically modulated injection of Ref. (3) (see Fig. 5). A range of order-one reduced pulse repetition rates $fL/\bar{U}_1$ were investigated and again no clear preference was found. It must be noted however that the repetition rates considered were all above the threshold value identified by Eqn. (1) below.

Impulsive surface injection was also investigated by Bons et al. (2) who used vortex generator jets on the blades of a linear cascade designed to mimic the flow separation possible in low-pressure turbines at high-altitude cruise. In that work, the authors identify a broad range of pulse repetition rates wherein the reduction in wake loss is independent of duty cycle and go on to demonstrate effective separation control with duty cycles as low as 10 percent. These results suggest the possibility of further lessening the implementation penalties associated with impulsive injection by reducing both the duty cycle and pulse repetition rate. Culley et al. (5) present data at both fixed pulse repetition rate and fixed pulse duration relevant to such an approach. The results are limited due to a difficulty in maintaining a constant injection velocity (subsequently addressed) over widely varying ranges of duty cycles. Even so the findings are generally consistent with those of Bons et al. (2) and justify a further investigation of this approach.

Current Work

Building on the preliminary results of Culley et al. (5), intra-stage total pressure data were taken for several pulse durations over a wide range of pulse repetition rates. The metric used to evaluate the benefit of impulsive injection to compressor performance is the total pressure loss coefficient which is given as

$$\omega = \frac{P_1 - P_2}{P_1 - p_1} + \frac{\dot{m}_{jet}}{\dot{m}_1}\frac{\bar{P}_{jet} - P_2}{P_1 - p_1}$$

per vane passage. This expression accounts for losses due to viscous dissipation within the vane boundary layers as well as mixing losses generated between the injected jet and the free stream. The former loss mechanism decreases as the boundary layer reattaches to the suction surface while the latter increases as the injection duty cycle is increased.

The time-average total pressure loss coefficient at 30 percent of span is plotted in Fig. 6. The source pressure p_{acc} for this data was held constant (at approximately 83 kPa) to produce a fixed instantaneous injection velocity. Despite considerable data scatter – due primarily to the embedded nature of the flow under consideration – some general trends are evident. For the four smallest pulse durations, the total pressure loss initially decreases with increasing pulse repetition rate f. The decrease continues with a slope only weakly dependent on pulse duration τ until f reaches approximately 200 Hz (or equivalently $F^+ \approx 0.488$) after which point the loss coefficient begins to level off.

This initial behavior is in agreement with that reported by Bons et al. (2) where the effectiveness of low frequency/small duty cycle pulsed injection is linked to the ejection of bound vorticity at the beginning of each jet pulse combined with the long recovery time of the locally re-energized boundary layer. According to this conjecture, the shed vorticity promotes cross-stream momentum redistribution as it propagates downstream leaving behind a re-attached boundary layer that then slowly relaxes back to its naturally separated state. Since ejection of the

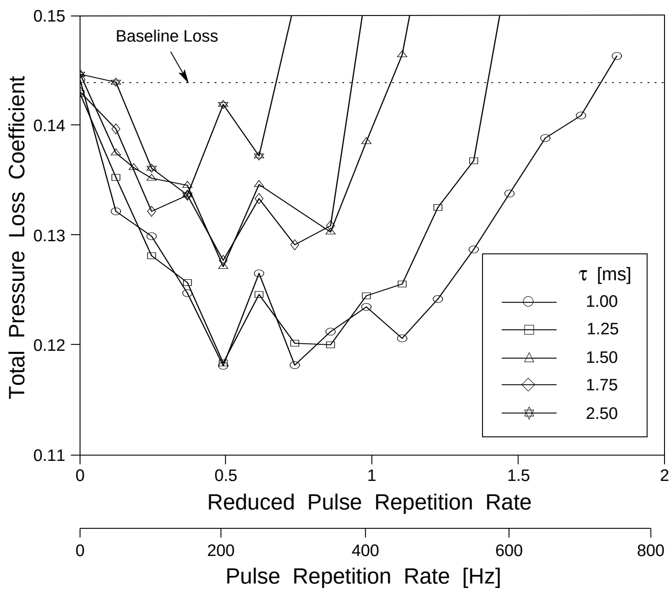

Figure 6. VARIATION OF LOSS WITH PULSE REPETITION RATE.

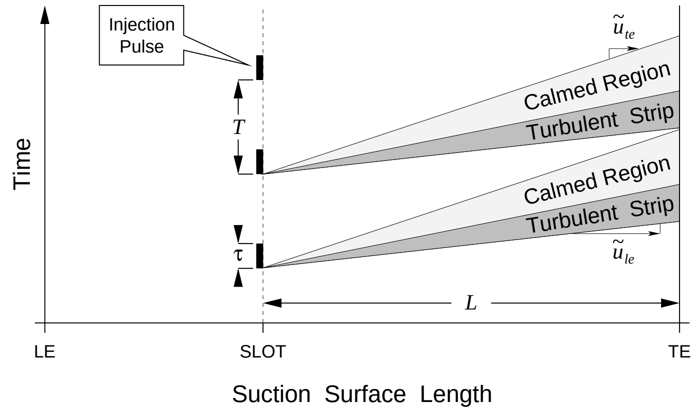

Figure 7. SPACE–TIME DIAGRAM OF IMPULSIVE INJECTION.

bound vorticity is largely independent of pulse duration, the resulting reduction in total pressure loss should display only a weak τ dependence. Similarly, since the conjecture implies the time-average state of the suction-surface flow depends chiefly on the lag between the relaxation of the local boundary layer and the shedding of the next pulse-induced vortex, an initially linear increase in loss reduction with pulse repetition rate is expected.

The low-repetition-rate data in Fig. 6 support the view that mixing enhancement is the primary mechanism by which an injection pulse re-energizes – if only temporarily – the local boundary layer. Mixing between the low-momentum near-wall fluid and the free stream is supposed to occur within a pulse-induced vortical disturbance as it propagates downstream. Such a disturbance is easily provoked by a short injection pulse applied to the decelerating boundary layer that precedes separation onset (8). The pulse excites a wide spectrum of simple waves each of which, while linear, grows or decays according to its ability to extract energy from the local time-average flow. The growing waves (i.e. Tollmien–Schlichting waves if the surrounding boundary layer is laminar) combine to form a linear wave packet that spreads as it travels downstream eventually becoming turbulent once nonlinear effects come into play (15). A propagating turbulent spot (or strip) so formed together with its trailing "calmed" region comprise the supposed pulse-induced region of re-energized flow.

The initial stages in the formation of an artificially generated turbulent spot are known to be influenced by properties of the triggering perturbation (eg. the pulse momentum and vorticity) but the spot's subsequent evolution depends only on the character of the flow into which it propagates (7, 8). It is assumed here that the spot-formation process is rapid enough to leave such large-scale time-average responses as the change in the total pressure loss across the airfoil unaffected. No attempt was made in the current set of experiments to track the pulse-induced disturbance through the stator-vane boundary layer nor could the precise state of that boundary layer be determined from the data collected. However results gathered in a similar low-speed research compressor (11) suggest that the boundary layer is transitional and at 35 percent of chord where the pulse is introduced only intermittently turbulent.

Analogous to the fixed-source approximation used by Mayle and Dullenkopf (10) to describe wake-induced transition, the time-average effect of impulsive surface injection on the stator-vane boundary layer is modeled here by assuming each jet pulse initiates a fully formed turbulent strip at the injection slot. The model does not explicitly address the receptivity of the local adverse-pressure-gradient boundary layer to unsteady excitation nor does it identify an optimal excitation frequency. It simply assumes that the broadband disturbance introduced by each injection pulse is sufficient to trigger the immediate formation of a turbulent strip within the local boundary layer.

From this simple model, an estimate of the minimum repetition rate necessary for a pulse disturbance to reach its predecessor before the latter is swept off the flow-control vane can be obtained (see Fig. 7),

$$f \approx \frac{\tilde{u}_{le}\tilde{u}_{te}}{\tilde{u}_{le} - \tilde{u}_{te}} \frac{1}{L}, \tag{1}$$

where $\tilde{u}_{le}$ and $\tilde{u}_{te}$ are the convection speeds of the leading edge of the pulse-induced turbulent strip and the trailing edge of its attendant "calmed" region, respectively. Both speeds are affected by the surface pressure gradient and laminar/turbulent state of the boundary layer into which the pulse disturbance propagates with

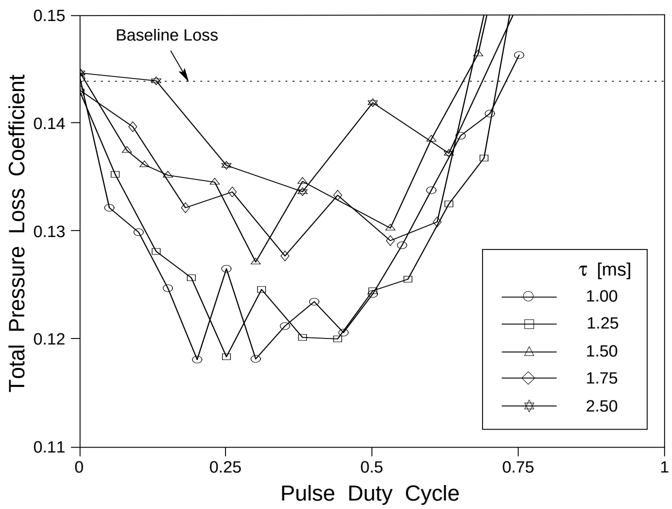

Figure 8. VARIATION OF LOSS WITH PULSE DUTY CYLCE.

$\tilde{u}_{te}$ being most strongly influenced (9). However, if these effects are ignored and the standard values of Ref. (16) used, i.e. $\tilde{u}_{le} = 0.88\bar{U}_1$ and $\tilde{u}_{te} = 0.3\bar{U}_1$, Eqn. (1) predicts $f \approx 186$ Hz (or equivalently $F^+ \approx 0.455$) which is roughly equal to the value in Fig. 6 where the loss coefficient curves begin to level off.

That an optimal level of flow control should be achieved at the repetition rate estimated by Eqn. (1) is consistent with observations made in Refs. (17) and (18) based on wind tunnel investigations of isolated airfoils. Seifert et al. (17) concluded that pulsed blowing is most effective at controlling separation when one to two pulse disturbances reside at any time on the airfoil downstream of the injection slot. The space–time diagram of Fig. 7 shows that Eqn. (1) satisfies this criterion. Zaman and Culley (18) found that the vortex shedding frequency in the wake of the uncontrolled airfoil sets the low-frequency limit on effective stall control using unsteady excitation. The pulse repetition rate estimated by Eqn. (1) is consistent with this finding because it represents the minimum rate to produce a continuous disruption in the flow field at the airfoil trailing edge and that disruption could give rise to the observed correlation by modifying the global instability that causes vortex shedding (19).

Figure 11 of Bons et al. (2) shows how the naturally separated state re-emerges by expanding forward from the trailing edge after the vortical disturbance triggered by a single injection pulse is swept off the airfoil. Pulse repetition rates sufficient to provide an uninterrupted supply of pulse-induced disturbances at the stator-vane trailing edge might therefore be expected to yield a fully attached suction-surface boundary layer and consequently a fixed reduction in total pressure loss.

This expectation is not borne out by the data plotted in Fig. 6. Instead each set of fixed τ data peels away from the "constant" loss level and undergoes a decline as the repetition rate corresponding to a duty cycle of 50 percent (i.e. $f = 0.5/\tau$) is exceeded. This behavior is more clearly demonstrated in Fig. 8 which contains the data of Fig. 6 replotted against the pulse duty cycle d. The prediction of a flat response in total pressure loss is predicated on each injection pulse behaving as an isolated event which is certain to be violated as f (and hence the duty cycle) becomes sufficiently large. Nevertheless Bons et al. (2) report a fixed wake loss coefficient for duty cycles all the way up to 100 percent, i.e. steady injection. This highlights a significant difference between that investigation and the present one.

The instantaneous injection velocity (or jet blowing) ratios considered in Ref. (2) are all above unity and so well within the range where the steady momentum introduced by the injection stream promotes boundary-layer re-attachment. This explains the reported effectiveness of their pulsed injection at 100 percent duty cycle. In the present investigation, reducing the net amount of injected mass is a primary objective so the instantaneous injection velocities used here (as well as those considered in Ref. (5)) are below the threshold at which steady injection is beneficial. The per-pulse injected-mass fraction relative to passage through flow $\dot{m}_\tau/\dot{m}_1$ for the data in Fig. 6 is approximately 0.17 percent which Fig. 4 shows to be detrimental when applied at 100 percent duty cycle. It is therefore concluded that the stream of time-mean moment introduced with the present impulsive injection is too low to re-energized the boundary layer and instead contributes to the total pressure loss.

In view of this, the data in Figs. 6 and 8 merely reflect the competition between the benefits of injection-induced mixing and the detriments of introducing additional low-momentum fluid. The balance shifts from the former to the latter as the duty cycle increases through 50 percent. A simple analytic description of this shift can be obtained by modeling the injection stream as a periodic train of constant amplitude pulses,

$$u_{jet}(t) = b\bar{U}_1 \sum_{n=0}^{\infty} \left[h(t-nT) - h(t-nT-\tau)\right],$$

and computing the period-averaged injected-momentum coefficient,

$$C_\mu \equiv \frac{A_{jet}}{sL}\frac{1}{T}\int_0^T \frac{u_{jet}^2}{\bar{U}_1^2}\mathrm{d}t = \frac{A_{jet}}{sL}\,\frac{\bar{u}_{jet}^{\,2} + u_{jet}'^{\,2}}{\bar{U}_1^2}, \qquad (2)$$

where h is the Heaviside step function and the mean and fluctuating components of the injection velocity are given as

$$\bar{u}_{jet} \equiv \frac{1}{T}\int_0^T u_{jet}\mathrm{d}t = b\bar{U}_1 d,$$

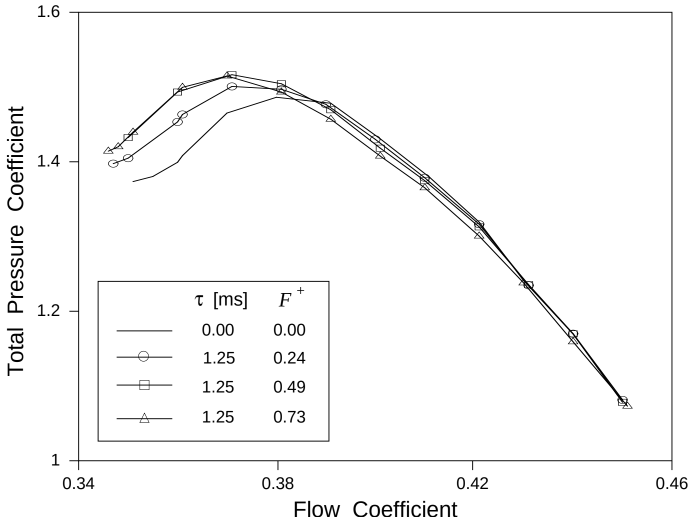

Figure 9. VARIATION OF WAKE WITH FLOW COEFFICIENT.

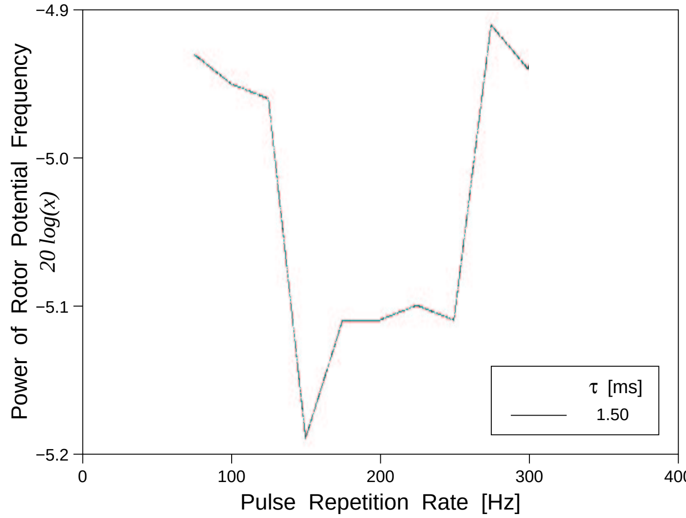

Figure 10. POWER SPECTRAL DENSITY OF CASING PRESSURE.

and

$$u'_{jet} \equiv \left[\frac{1}{T}\int_0^T (u_{jet} - \bar{u}_{jet})^2 \mathrm{d}t\right]^{1/2} = b\bar{U}_1\sqrt{d(1-d)},$$

respectively. Consistent with Figs. 6 and 8, Eqn. (2) predicts that at small duty cycles the contribution from the fluctuating component exceeds that of the mean component but that the latter quickly dominates the former as the duty cycle passes 50 percent.

The falloff in loss reduction for duty cycles greater than 50 percent can significantly shorten the range of pulse repetition rates where separation control is most effective. As the pulse duration τ increases, this trend becomes more pronounced and eventually prevents reaching the optimal level of flow control, i.e. the duty cycle exceeds 50 percent before the threshold repetition rate estimated by Eqn. (1) is reached. By that estimate, this situation occurs for pulse durations greater than 2.7 ms. The results at $\tau = 2.5$ ms shown in Fig. 6 suggest that it may actually begin at somewhat smaller τ, although the loss data could also be affected by a decline in instantaneous injection velocity at the tail end of this longer pulse duration. The decline results from a drop in source pressure p_{acc} that also occurred at the shorter pulse durations when the duty cycle became sufficiently large and lead to an under prediction of the loss reduction by as much as 10 percent.

It turns out that injection-induced mixing does not always benefit the compressor performance. Figure 9 shows the total pressure coefficient behind the flow-control vane as a function of flow coefficient ϕ for a fixed pulse duration and various pulse repetition rates. The data was collected at a single point (30 percent of span and 43 percent of pitch) that is shown in Ref. (5) to be representative of the general state of the stator-vane wake. As ϕ increases from the nominal setting of 0.36, the recovery of total pressure achieved with impulsive injection slowly declines until $\phi \approx 0.39$ after which the injection has an adverse effect on the pressure recovery and consequently the vane performance. This change is believed to coincide with the change in state of the baseline suction-surface boundary layer from separated to attached. While the uncontrolled flow along the restaggered vane is prone to separation, impulsive injection reduces the total pressure loss by re-energizing the boundary layer, but once ϕ becomes sufficient to yield a fully attached flow, that same injection tends to increase the loss by increasing viscous dissipation.

The behavior exhibited in Fig. 9 highlights the importance of activating the separation control on an as needed basis. Developing a non-intrusive technique for detecting stator-vane separation is the subject of a separate investigation taking place concurrently in the LSAC facility. Outcomes of that effort will be reported elsewhere, however some preliminary results are presented here since they provide additional confirmation of the trends observed in Fig. 6. Static pressure data was collected from a transducer located in the compressor casing next to the suction surface of the flow-control vane at 85 percent of chord. The pressure signal is used to identify the state of the stator-vane boundary layer by exploiting a correlation between the power in the first harmonic of the downstream-rotor-blade passage frequency and the strength of the stator-vane wake. The interested reader is referred to Ref. (3) for a description of the aerodynamic basis for this correlation. The power spectral density of the pressure signal at the blade passage frequency is plotted against pulse repetition rate in Fig. 10 for a pulse duration of 1.5 ms. The results are generally consistent with those of Fig. 6 in that, as the repetition rate increases, there is an initial decline in spectral density fol-

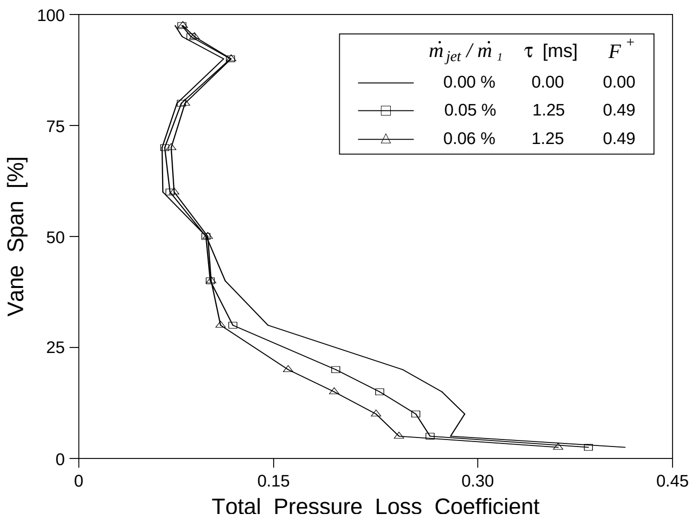

Figure 11. VARIATION OF LOSS WITH VANE SPAN.

lowed by an approximate leveling off and then a sharp increase. All of which correlates with the reduction, full suppression and eventual return of the stator-vane separation.

Thus far the success of impulsive surface injection has been judged on local reductions in the total pressure loss across the flow-control vane, i.e. reductions determined from circumferential surveys taken at 30 percent of span. To confirm the benefits of the proposed flow-control treatment it is necessary to consider the variation in loss across the entire vane span. Figure 11 shows that variation at a fixed pulse duration and repetition rate for two period-averaged injected-mass fractions $\dot m_{jet}/\dot m_1$. As indicated above, the total pressure loss across the restaggered stator vane is greatest near the hub and it is in this region where the injection (through a slot opening extending from 10 to 36 percent of span) is most beneficial. It is interesting to note however that the reduction in total pressure loss persists out to almost 50 percent of span.

DISCUSSION

The results presented here provide a guide for developing durable, economic impulsive-injection-based flow-control treatments capable of suppressing stator-vane separation in multistage axial-flow compressors. They show that the combined goals of reducing net injected mass and limiting actuator frequency can be met by using the shortest realizable pulse duration at a pulse repetition rate just sufficient to ensure a continuously attached suction-surface boundary layer. This combination yields the lowest duty cycle and hence smallest net injected mass while still fully suppressing the stator-vane separation.

The next challenge in the current effort is the installation of flow-control stators around the entire compressor annulus. A full-annulus treatment will allow a truer assessment of the benefits of separation control with respect to wider operability range and increased per-stage pressure rise. Before beginning such an undertaking, it is advisable to investigate the proposed compressor's performance and stability characteristics through numerical simulation. As most CFD codes for analyzing multistage turbomachinery compute time-average flow fields, this necessitates developing a mathematical model for the time-average effect of impulsive surface injection.

The numerical simulation of multistage axial-flow compressors with steady surface injection has been undertaken at NASA Glenn Research Center. To extend that work to impulsive surface injection requires accounting for the enhanced mixing provoked by the fluctuating component of the injection stream. As indicated above, the actuation parameters of most interest lie in the range where each injection pulse behaves as an isolated event. Moreover, the effect on the boundary layer of each pulse appears to mimic the passage of a turbulent spot. A periodic train of injection pulses should then produce a boundary-layer effect analogous to that occurring in flow over an embedded airfoil where turbulent spots are periodically induced by the shed wakes of upstream blades.

The analogy with periodic wake-induced transition suggests the time-average effect of impulsive injection may be (in addition to introducing a small amount of low-momentum fluid) merely to increase the fraction of time the local boundary layer is turbulent. If true this would have the effect of shifting the transition to fully developed turbulence forward toward the injection slot. Adamczyk et al. (20) demonstrates the sensitivity of multistage simulations based on the average-passage model to the assumed state of the blade boundary layers. As this sensitivity is likely to grow with the potential for boundary-layer separation, a first approximation to the time-average effect of optimal impulsive injection might be to simply augment the eddy viscosity downstream of the injection slot with a factor proportional to the fluctuating part of the injected momentum.

CONCLUSIONS

As part of an ongoing program to develop robust, practical, fluidic-based methods for controlling stator-vane separation in axial-flow compressors, an investigation of impulsive surface injection was carried out. Similarities in the way injected air is introduced on the stator-vane suction surface and the methods used to artificially trigger turbulent spots in wind tunnel experiments suggest that impulsive surface injection periodically initiates strips of turbulence ahead of the region of separated flow. It is argued that these injection-triggered turbulent strips effect the local boundary layer in a manner analogous to wake-induced transition which is known to delay stator-vane separation in multistage compressors. The advantage impulsive surface injection provides is the ability to control both the frequency and origin of the triggered turbulent regions.

Measured total pressure losses across the embedded flow-control vanes reveal an eventual decline in the effectiveness of impulsive surface injection with increasing pulse duty cycle. This behavior is linked to the relatively low injection velocities used to limit the net amount of injected mass. At low injection velocity, the fluid packet introduced with each injection pulse lacks momentum sufficient to re-energize the decelerating boundary layer and instead further aggravates the flow separation. This adverse effect is overcome at low duty cycles by the enhanced mixing associated with the injection triggered turbulent strips but as the duty cycle exceeds 50 percent the ability to suppress flow separation rapidly declines. Competition between the two effects results in a finite band of pulse repetition rates at each pulse duration where impulsive surface injection is most effective.

NOMENCLATURE

A_{jet} = total area of injection slots
b = instantaneous injection velocity ratio $= u_{jet}/\bar{U}_1$
C_μ = period-averaged injected-momentum coefficient
c = chord $= 9.4$ cm
d = duty cycle $= \tau/T$
F^+ = reduced pulse repetition rate $= fL/\bar{U}_1$
f = dimensional pulse repetition rate $= 1/T$
L = distance from injection site to vane trailing edge $= 0.65c$
$\dot{m}_1$ = free-stream mass-flow rate per vane passage
$\dot{m}_\tau$ = per-pulse injected mass-flow rate
$\dot{m}_{jet}$ = period-averaged injected mass-flow rate $= d\,\dot{m}_\tau$
p_{acc} = source pressure set by accumulator
$\bar{P}_{jet}$ = period-averaged total pressure internal to flow-control vane
P_1 = area-averaged total pressure ahead of vane passage
P_2 = area-averaged total pressure behind vane passage
p_1 = area-averaged static pressure ahead of vane passage
s = vane span $= 12.2$ cm
T = pulse (or actuation) period $= 1/f$
t = time
$\bar{U}_1$ = mean free-stream velocity ahead of vane passage $= 25$ m/s
u_{jet} = instantaneous injection velocity
$\bar{u}_{jet}$ = period-averaged injection velocity
u'_{jet} = root-mean-square of $u_{jet} - \bar{u}_{jet}$
$\tilde{u}_{le}$ = leading-edge speed of pulse-induced disturbance
$\tilde{u}_{te}$ = trailing-edge speed of pulse-induced disturbance
τ = pulse duration = solenoid on time
ϕ = flow coefficient = *mean inlet velocity / tip speed*
ψ = pressure rise coefficient
ω = total pressure loss coefficient

REFERENCES

[1] Carter, C., Guillot, S., Ng, W., and Copenhaver, W., 2001. "Aerodynamic Performance of a High-Turning Compressor Stator with Flow Control". AIAA Paper number 2001–3973.

[2] Bons, J.P., Sondegaard, R., and Rivir, R.B., 2002. "The Fluid Dynamics of LPT Blade Separation Control Using Pulsed Jets". *ASME Journal of Turbomachinery*, Vol. 124, pp. 77–85.

[3] Culley, D.E., Bright, M.M., Prahst, P.S., and Strazisar, A.J., 2003. "Active Flow Separation Control of a Stator Vane Using Surface Injection in a Multistage Compressor Experiment". *ASME Journal of Turbomachinery*, Vol. 126, pp. 24–34.

[4] Kirtley, K.R., Graziosi, P., Wood, P., Beacher, B., and Shin, H.W., 2004. "Design and Test of an Ultra-Low Solidity Flow Controlled Compressor Stator". ASME GT2004–53012.

[5] Culley, D.E., Braunscheidel, E.P., and Bright, M.M., 2005. "Impulsive Injection for Compressor Stator Separation Control". AIAA Paper number 2005–3633.

[6] Glezer, A., Amitay, M., and Honohan, A.M., 2005 "Aspects of Low- and High-Frequency Actuation for Aerodynamic Flow Control". *AIAA Journal*, Vol. 43, pp. 1501–1511.

[7] Wygnanski, I.J., Sokolov, M., and Friedman, D., 1976. "On a Turbulent Spot in a Laminar Boundary Layer". *Journal of Fluid Mechanics*, Vol. 78, pp. 785–819.

[8] Seifert, A., and Wygnanski, I.J., 1995. "On Turbulent Spots in a Laminar Boundary Layer Subjected to a Self-Similar Adverse Pressure Gradient". *Journal of Fluid Mechanics*, Vol. 296, pp. 185–209.

[9] Gostelow, J.P., Melwani, N., and Walker, G.J., 1996. "Effects of Streamwise Pressure Gradient on Turbulent Spot Development". *ASME Journal of Turbomachinery*, Vol. 118, pp. 737–743.

[10] Mayle, R.E., and Dullenkopf, K., 1991. "More on the Turbulent-Strip Theory for Wake-Induced Transition". *ASME Journal of Turbomachinery*, Vol. 113, pp. 428–432.

[11] Halstead, D.E., Wisler, D.C., Okiishi, T.H., Walker, G.J., Hodson, H.P., and Shin, H.-W., 1997. "Boundary Layer Development in Axial Compressors and Turbines: Parts 1–4". *ASME Journal of Turbomachinery*, Vol. 119, pp. 114–127; 426–444; 225-237; 128–139.

[12] Wasserbauer, C.A., Weaver, H.F., and Senyitko, R.G., 1995. "NASA Low-Speed Axial Compressor for Fundamental Research". NASA TM 4635.

[13] Wellborn, S., and Okiishi, T., 1999. "The Influence of Shrouded Stator Cavity Flows on Multistage Compressor Performance". *ASME Journal of Turbomachinery*, Vol. 121, pp. 486–498.

[14] Wisler, D.C., 1977. "Core Compressor Exit Stage Study: Volume I – Blade Design". NASA CR 135391.

[15] Gaster, M., and Grant, I., 1975. "An Experimental Investigation of the Formation and Development of a Wave Packet in a Laminar Boundary Layer". *Proceedings of the Royal Society of London A*, Vol. 347, pp. 253-269.

[16] Schubauer, G.B., and Klebanoff, P.S., 1955. "Contributions on the Mechanics of Boundary-Layer Transition". NACA TR 1289.

[17] Seifert, A., Daraby, A., Nishri, B., and Wygnanski, I., 1993. "The Effects of Force Oscillations on the Performance of Airfoils". AIAA Paper number 93–3264.

[18] Zaman, K.B.M.Q., and Culley, D.E., 2006. "A Study of Stall Control Over an Airfoil Using Synthetic Jets". AIAA Paper number 2006–0098.

[19] Huerre, P., and Monkewitz, P.A., 1990. "Local and Global Instabilities in Spatially Developing Flows". *Annual Review of Fluid Mechanics*, Vol. 22, pp. 473–537.

[20] Adamczyk, J.J., Hathaway, M.D., Shabbir, A., and Wellborn, S.R., 1998. "Numerical Simulation for Multi-Stage Turbomachinery Flows". Published in RTO MP-8.

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David W. Wundrow, Edward P. Braunscheidel, Dennis E. Culley, and Michelle M. Bright

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National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
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Control of flow separation using impulsive surface injection is investigated within the multistage environment of a low speed axial-flow compressor. Measured wake profiles behind a set of embedded stator vanes treated with suction-surface injection indicate significant reduction in flow separation at a variety of injection-pulse repetition rates and durations. The corresponding total pressure losses across the vanes reveal a bank of repetition rates at each pulse duration where the separation control remains nearly complete. This persistence allows for demands on the injected-mass delivery system to be economized while still achieving effective flow control. The response of the stator-vane boundary layers to infrequently applied short injection pulses is described in terms of the periodic excitation of turbulent strips whose growth and propagation characteristics dictate the lower bound on the band of optimal pulse repetition rates. The eventual falloff in separation control at higher repetition rates is linked to a competition between the benefits of pulse-induced mixing and the aggravation caused by the periodic introduction of low-momentum fluid. Use of these observations for impulsive actuator design is discussed and their impact on modeling the time-average effect of impulsive surface injection for multistage steady-flow simulation is considered.

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